REMARKS

Favorable reconsideration of this application, as presently amended and in light of the following discussion, is respectfully requested.

Claims 1-19 are currently pending. Claim 16 has been amended by the present amendment. The changes to Claim 16 are supported by the originally filed specification and do not add new matter.

In the outstanding Office Action, Claim 16 was objected to as containing various informalities; and Claims 1-19 were rejected under 35 U.S.C. § 102(a) as being anticipated by Shahriar et al. ("Solid State Quantum Computing Using Spectral Holes") (hereinafter "the Shahriar et al. reference").

Regarding the objection to Claim 16, that claim has been amended in the manner suggested in the Office Action. Accordingly, the objection to Claim 16 is believed to have been overcome.

The Shahriar et al. reference, which is asserted against all pending claims in the present application, has an effective reference date of July, 2000. The actual U.S. filing date of the present application is November 17, 2000. However, the present application claims priority under 35 U.S.C. § 119 to Japanese Patent Application No. 11-328333, filed November 18, 1999. Therefore, in order to perfect Applicants' claim for foreign priority in the present application, submitted herewith is a certified English-language translation of Japanese Patent Application No. 11-328333. Thus, Applicants respectfully submit that the Shahriar et al. reference does not qualify as *prima facie* prior art against the claims in the present application. Accordingly, Applicants respectfully submit that the rejection under 35 U.S.C. § 102 should be withdrawn.

Thus, it is respectfully submitted that independent Claims 1 and 14 (and all associated dependent claims) patentably define over the Shahriar et al. reference.

Consequently, in view of the present amendment and in light of the above discussion, the outstanding grounds for rejection are believed to have been overcome. The application as amended herewith is believed to be in condition for formal allowance. An early and favorable action to that effect is respectfully requested.

Respectfully submitted,

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Docket No.: 199858US-620-39-2SRD

IN THE UNITED STATES PATENT & TRADEMARK OFFICE

IN RE APPLICATION OF: Kouichi Ichimura et al.

SERIAL NO: 09/714,193

FILED: November 17, 2000

FOR: METHOD FOR QUANTUM INFORMATION PROCESSING AND QUANTUM INFORMATION PROCESSOR

TRANSLATION OF DOCUMENT

ASSISTANT COMMISSIONER FOR PATENTS
WASHINGTON, D.C. 20231

SIR:

Kenji Kobayashi, a translator residing at 2-46-10, Gokonishi, Matsudo-shi, Chiba-ken, Japan, hereby states:

(1) that I know well both the Japanese and English languages;

(2) that I translated the attached document identified as corresponding to Patent Application No. **11-328333** filed in Japan on **November 18, 1999** from Japanese to English;

(3) that the attached English translation is a true and accurate translation to the best of my knowledge and belief.

DATE: April 8, 2004

BY: Kenji Kobayashi

Kenji Kobayashi

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[Reference Number]	A009907045
[Filing Date]	November 18, 1999
[To]	Commissioner, Patent Office
[International Patent Classification]	G06E 1/00
[Title of the Invention]	QUANTUM INFORMATION PROCESSING METHOD AND QUANTUM INFORMATION PROCESSOR
[Number of Claims]	10
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[List of Items Submitted]

[Name of Item]	Specification	1
[Name of Item]	Drawing	1
[Name of Item]	Abstract	1
[Necessity of Proof]	Necessary	

[Document] SPECIFICATION

[Title of the Invention] QUANTUM INFORMATION PROCESSING METHOD AND QUANTUM INFORMATION PROCESSOR

[What is Claimed is:]

[Claim 1] A quantum information processing method which expresses and processes information by quantum states of a plurality of physical systems each having at least three energy states, the method characterized by comprising:

two transitions of transitions between respective energy states of each physical system being optically allowed, and expressing bit information of each physical system by a quantum state expressed by either one of two states constituting a remaining transition or by both superposition states;

irradiating two-wavelength pulse lights corresponding to the transition energy of the two transitions in a temporarily superposed state to change the quantum state of individual physical system or the entire physical systems; and

selecting a physical system to change the quantum state through a frequency of the pulse light.

[Claim 2] The quantum information processing method according to claim 1, characterized in that a plurality of physical systems expressing information are held in a solid substance, and the transition energy of the two transitions is different for respective physical systems according to a surrounding local field of the physical systems.

[Claim 3] The quantum information processing method according to claim 1, characterized in that a plurality of physical systems expressing information consist of ions contained in a solid substance, and two of the three energy states of each physical system are neighboring two levels generated by hyperfine structure splitting due to the nuclear spin of the ion.

[Claim 4] The quantum information processing method according to claim 1 or 2, characterized in that the quantum states of a plurality of physical systems whose transition frequencies are contained in a given range are collectively changed by a pulse light having corresponding one or two transition frequencies as a center frequency.

[Claim 5] The quantum information processing method according to any one of claims 1 to 4, characterized in that quantum information processing is performed by computation.

[Claim 6] The quantum information processing method according to any one of claims 1 to 4, characterized in that a plurality of physical systems expressing information are arranged in a resonator having two or more light reflection surfaces to cause quantum-mechanical interaction between the plurality of physical systems through a resonator mode.

[Claim 7] The quantum information processing method according to claim 6, characterized in that a plurality of physical systems expressing information are atoms, ions or molecules in a solid substance, and the surface of the solid substance is polished to form a multi-layered coating for

light reflection thereon, which is used as a light reflection surface of the resonator.

[Claim 8] A quantum information processor characterized by comprising:

a plurality of physical systems expressing information through quantum states, each of which having at least three energy levels, in which two transitions of the transitions between respective energy levels are optically allowed, and the transition frequencies of each physical system is different, distributing with an inhomogeneous width; and

a resonator holding the plurality of physical systems inside, and having a resonator mode that resonates with one transition of the optically allowed transitions within a range of the inhomogeneous width of the transition frequency.

[Claim 9] The quantum information processor according to claim 8, characterized by comprising:

a light source of the coherent light for irradiating a plurality of physical systems to operate or detect the quantum state, and having two or more different frequencies resonant with two optically allowed transitions within a range of the inhomogeneous width of the transition frequency; and

a detector for detecting light transmission intensity of the light irradiated on the physical system or light emission intensity of the physical system.

[Claim 10] The quantum information processor according to claim 8, characterized by further comprising

means for applying a magnetic field or electric field on the physical systems in accordance with changes of intensity of the light irradiated on the physical systems.

[Detailed Description of the Invention]

[0001]

[Technical Field of the Invention]

The present invention relates to a method for quantum information processing using a solid-state element, and more particularly to a method for quantum information processing in which operation is optically performed and which can attain high scalability of quantum bits and to a quantum information processor.

[0002]

[Prior Art]

A new information processing method is proposed for performing information processing in quantum processes in which quantum states of an atom such as a ground state and an excited state are set so as to correspond to "0" and "1" and bits are expressed by using each quantum state $|0\rangle$ or $|1\rangle$ or a superposition state $\alpha|0\rangle + \beta|1\rangle$ thereof (where α and β are complex numbers). Quantum computers based on such quantum information processing are proposed and formulated by Bennioff (P. Bennioff, Phys. Rev. Lett., 48, 1581 (1982)), Feynman (R. P. Feynman, Found. Phys., 16, 507 (1986)), and Deutsch (Proc. Roy. Soc. London, Ser. A400, 96 (1985)), and are now popularly studied.

[0003]

In a conventional computer (a classical computer), a bit carrying information takes a value of "0" or "1". On the contrary, a bit in the quantum computation can take a value of not only $|0\rangle$ or $|1\rangle$ but also their superposition state $\alpha|0\rangle + \beta|1\rangle$. Such a bit is called a quantum bit (qubit). In the quantum computation, a plurality of (N) qubits is simultaneously dealt with and the whole qubits are subjected to unitary transformation called a gate operation to perform computation. Since the N qubits simultaneously express 2^N numbers, it becomes possible to make 2^N parallel computations. Therefore, it is possible to make extremely rapid computations for a certain problem.

[0004]

Thus, the quantum computer has a potential capacity exceeding that of the classical computer in quality and is expected as the future information processing technology and computing technology. However, it has been considered that it is extremely difficult to realize the quantum computer. This is because it is difficult in practice to retain the superposition quantum states during computations and prevent a change other than the intended change of states by the gate operation from occurring. Further, in the quantum computation, it is necessary to couple the qubits to each other with retaining quantum coherency, but this is also difficult.

[0005]

However, so far, some physical systems which make it possible to realize the quantum computation are proposed, and recently, some experiments are demonstrated.

[0006]

One example is a method using ion trap that is theoretically proposed by Cirac and Zoller (J. I. Cirac and P. Zoller, Phys. Rev. Lett., 74, 4091 (1995)). In this method, individual ions are separated from one another by a distance of the order of micrometer or more and held in an electromagnetic trap at extremely low temperatures, and electron excited levels and a collective vibrational level of the ions are used. The collective vibrational level is a vibrational excited state related to the center-of-mass motion of all of the ions and serves to couple individual ions, i.e., qubits. An independent ion in the trap is hard to receive unnecessary interaction from the external world, and can retain the superposition state for a long period of time, which is a major premise for the quantum computation. However, it is necessary to use a large-scale apparatus for the ion trap at extremely low temperatures and thus it is difficult to reduce the size of the element. Further, the qubit is distinguished based on the position of the ion and a spatially converged laser beam is irradiated to aim at the specified ion. Thus, since the processing operation is effected with the individual qubits distinguished from one another by selectively applying the laser beam to the

specified ion, it is necessary to separate the ions by a distance of at least approximately the wavelength of light, and therefore the integration of the elements and the scalability of the qubits are restricted.

[0007]

Proposal of an NMR quantum computer using a nuclear spin of an atom in a molecule as a qubit is known as another physical system which can be experimented (N. A. Gershenfeld, I. Chuang, Science, 275, 350 (1997)). In this method, a nuclear spin of an atom in a molecule is used as a qubit, based on an idea that a magnetic field is applied to molecules in a solution, thereby allowing energy levels of the nuclear spin to cause Zeeman splitting. Then, the computation is executed by operating the quantum state of the nuclear spin, i.e., the qubit by affecting a high-frequency electromagnetic field resonant with the split energy level. The degree of the Zeeman splitting is different depending on the types of atoms and also different depending on the position of the atom in the molecule even if the atoms are of the same type. Therefore, it becomes possible to select a nuclear spin resonant with the frequency of the high-frequency electromagnetic field and to operate a single qubit. In the NMR quantum computation, the computation up to three bits is demonstrated. However, in this method, since each molecule acts as one computer, there occurs a problem that the number of qubits cannot freely be increased.

[0008]

The above two examples are most advanced researches at present in which experiments for a quantum gate operation and execution of a simple computation algorithm are performed. However, as described above, for practical computation, a problem occurs in the scalability of the qubits. Further, in the above examples, a single ion in a trap or a nuclear spin of a molecule in a solution is used as a qubit. However, it is desired for an element to make quantum computation by use of solid-state qubits that can be easily dealt with and have an advantage in reduction in size and integration.

[0009]

As a study for realizing the quantum computation using a solid-state element, an experiment of a qubit using a Josephson junction is known (Y. Nakamura, Yu. A. Pashkin and J. S. Tsai, Nature, 398, 786 (1999)). Nakamura et al. have succeeded in creating a superposition state of two states different in the number of electrons by use of microelectrodes in superconductive states. However, in this case, an advanced fine fabricating process is required for formation of qubits and coupling between a plurality of qubits. Further, an effective method for coupling coherently a large number of qubits is not known.

[0010]

There is another proposal of qubit and quantum computation in which a metal atom or a molecule is held in fullerene and the electron states of a π electron of the

fullerene are utilized (Fukumi et al., Jpn. Pat. Appln. KOKAI Publication No. 10-254569). In this proposal, the phenomenon is utilized that light frequencies for exciting the π electron of respective fullerene molecules are different depending on the number of carbon atoms in the fullerene or the type of the metal atom or the molecule, and fullerene used as a qubit is selected according to the wavelength of irradiated light to perform a computing operation. In this method, the qubits are coupled by bonding the fullerene molecules with a carbon nanotube. In other words, an artificial molecule, in which the fullerene serves as an atom and the carbon nanotube serves as the interatomic bond, is used instead of the molecule in the NMR computer. However, since a highly fine fabricating technology or synthesis technology is required for coupling qubits in this method, it is considered difficult to attain scalability to a large number of qubits. Further, since two levels of the ground state and the excited state of the π electron coupled through an allowed transition are utilized for a qubit, decoherence by relaxation is easily caused, and therefore difficulty is expected in retaining the superposition state for a sufficiently long time necessary for computation.

[0011]

As described above, according to the conventional method, in a physical system in which it is possible to retain coherency for a long period of time and a simple gate operation has already been realized, a single ion in a trap

or a molecule in a solution is used. Therefore, it is hard to handle compared with the solid substance and also have difficulty in reduction in size and integration as elements, and further the scalability of the qubits is low. Further, in the proposal in which the solid-state element is used, since decoherence is rapidly caused because of the method for operating the qubits and a material constituting the qubits, it is difficult to maintain the superposition state. Moreover, it is necessary to couple qubits by use of a substance in the real space between the qubits, which requires an extremely fine fabricating technique and brings about difficulty in coupling a large number of qubits.

[0012]

In the circumstances described above, it is difficult to realize a device or apparatus for quantum information processing, which is represented by a quantum computer as a conventional method. Even if it is possible to realize it, the difficulty in the reduction in size of the apparatus and difficulty in scalability of the qubits as well as the lack of hyperfine fabricating technique could not realize a practical quantum information processor of a large number of qubits.

[0013]

[Object of the Invention]

As described above, in attempting a compact and practical quantum information processing that uses a large number of qubits, that can retain the superposition state for

a sufficiently long decoherence time and that is almost free from decoherence other than intended change of states during the gate operation, in order to use a solid-state element capable of reduction in size and integration, a rapid dechoherence is required in terms of a physical system for realizing a qubits, and also an advanced hyperfine fabricating technique and synthesis technique are required for wiring in terms of the forming of a device. Therefore, actually, the quantum information processing method excluding such disadvantages as realizing only a quantum information processor using a small number of bits, using a single ion and a molecule in a solution, has conventionally not been known.

[0014]

The present invention has been made in view of the foregoing circumstances and it is therefore an object of invention to provide a method for quantum information processing and a quantum information processor that is compact and practical and uses a large number of qubits, that can retain the superposition state for a sufficiently long decoherence time and that is almost free from decoherence other than intended change of states during the gate operation without requiring a difficult fine patterning process, chemical synthesis and a wiring by a crystal growth process.

[0015]

In other words, the object of the invention is to

provide a practical quantum information processing method and a quantum information processor which can distinguish and define qubits through frequency regions regardless of spatial positions of the qubits, requires no wiring or fine patterning process, has a high scale of integration and high scalability of qubits, and has good coherency.

[0016]

[Means for Achieving the Object]

In order to solve the foregoing problems, according to the present invention, there is provided a quantum information processing method (claim 1) which expresses and processes information by quantum states of a plurality of physical systems each having at least three energy states. The method is characterized by comprising: two transitions of transitions between respective energy states of each physical system being optically allowed, and expressing bit information of each physical system by a quantum state expressed by either one of two states constituting a remaining transition or by both superposition states; irradiating two-wavelength pulse lights corresponding to the transition energy of the two transitions in a temporarily superposed state to change the quantum state of individual physical system or the entire physical systems; and selecting a physical system to change the quantum state through a frequency of the pulse light.

[0017]

In the method of the present invention, since the

superposition state of the two levels, the transition between them being optically impossible, are used as a qubit expressing information, decoherence caused by relaxation can be alleviated. In addition, since a technique referred to as adiabatic passage applying population trapping can be used that enables to cause a change of superposition state of the lower two levels without excitation to the upper level for operating the qubit with utilizing two kinds of light, decoherence caused by relaxation from the upper level can be alleviated during a gate operation. Further, since a qubit is selected through a laser beam wavelength, a large number of qubits can be integrated in a space of a wavelength order.

[0018]

Another quantum information processing method (claim 2) of the present invention according to claim 1, is characterized in that a plurality of physical systems expressing information are held in a solid substance, and the transition energy of the two transitions is different for respective physical systems according to a surrounding local field of the physical systems. Hence, it is possible to realize quantum information processing which has small decoherency and a high scale of integration in a solid-state element.

[0019]

Another quantum information processing method (claim 3) of the present invention according to claim 1, is characterized in that a plurality of physical systems

expressing information consist of ions contained in a solid substance, and two of the three energy states of each physical system are neighboring two levels generated by hyperfine structure splitting due to the nuclear spin of the ion. Therefore, it is possible to realize quantum information processing which can compute a large number of processing steps during a long holding time of a superposition state of qubits using a solid-state element.

[0020]

Another quantum information processing method (claim 4) of the present invention according to claim 1 or 2, is characterized that the quantum states of a plurality of physical systems whose transition frequencies are contained in a given range are collectively changed by a pulse light having corresponding one or two transition frequencies as a center frequency. Thus, a large reading signal can be obtained, and since not a single but a plurality of particles express one qubit, error can be reduced.

[0021]

Another quantum information processing method (claim 5) of the present invention according to any one of claims 1 to 4, is characterized in that quantum information processing is performed by computation. Therefore, quantum computation with features realized through claims 1 to 4 can be performed.

[0022]

Another quantum information processing method (claim 6)

of the present invention according to any one of claims 1 to 4, is characterized in that a plurality of physical systems expressing information are arranged in a resonator having two or more light reflection surfaces to cause quantum-mechanical interaction between the plurality of physical systems through a resonator mode. Therefore, it is possible to couple the qubits regardless of positional relationships of physical systems to be the qubits in a solid-state element, and it is possible to wirelessly perform quantum information processing with a high scale of integration to select the qubits with angular frequencies of light without utilizing a difficult hyperfine fabricating technique.

[0023]

Another quantum information processing method (claim 7) of the present invention according to claim 6, is characterized in that a plurality of physical systems expressing information are atoms, ions or molecules in a solid substance, and the surface of the solid substance is polished to form a multi-layered coating for light reflection thereon, which is used as a light reflection surface of the resonator. Hence, it is possible to perform quantum information processing using qubits by a solid-state element having a small resonator, and it is also possible to enhance the coupling effect through the resonator since the resonator can be small.

[0024]

In the present invention, it is possible to use a spherical or disk-like solid substance, to form a coating on the curved surface thereof and to confine light inside the solid substance by total reflection.

[0025]

A quantum information processor (claim 8) of the present invention is characterized by comprising: a plurality of physical systems expressing information according to quantum states, each of which having at least three energy levels, in which two transitions of the transitions between respective energy levels are optically allowed, and the transition frequencies of each physical system is different, distributing with an inhomogeneous width; and a resonator holding the plurality of physical systems inside, and having a resonator mode that resonates with one transition of the optically allowed transitions within a range of the inhomogeneous width of the transition frequency.

[0026]

Therefore, provided is a quantum information processor that is compact and practical and uses a large number of qubits, that can retain the superposition state for a sufficiently long decoherence time and that is almost free from decoherence other than intended change of states during the gate operation without requiring a difficult fine patterning process, chemical synthesis and a wiring by a crystal growth process.

[0027]

Another quantum information processor (claim 9) of the present invention according to claim 8, is characterized by comprising: a light source of the coherent light for irradiating a plurality of physical systems to operate or detect the quantum state, and having two or more different frequencies resonant with two optically allowed transitions within a range of the inhomogeneous width of the transition frequency; and a detector for detecting light transmission intensity of the light irradiated on the physical system or light emission intensity of the physical system.

[0028]

Therefore, the quantum information processor is configured to provide a light source for data input, computation or result readout, and thus capable of converting the detection result from a detector into, for example, an electric signal or record the detection result.

[0029]

Another quantum information processor (claim 10) of the present invention according to claim 8, is characterized by comprising a means for applying a magnetic field or electric field on the physical systems in accordance with changes of intensity of the light irradiated on the physical systems. Thus, it is possible to split degenerated levels to use them for holding the quantum states, which enables quantum information processing with a large scale of freedom.

[0030]

[Embodiments of the Invention]

A quantum information processing method of the present invention has the following three major features.

[0031]

(1) Physical systems each having three levels are used as qubits and, when the qubits are operated by use of light, a technique called adiabatic passage is used utilizing population trapping induced where two-wavelength light beams are applied to the three-level systems.

[0032]

(2) A plurality of physical systems having different transition frequencies between the levels are used as qubits, and in operation of qubits by use of light, individual qubits can independently be operated by resonating a light frequency with the transition frequency of a desired qubit.

[0033]

(3) Transitions of the respective qubits are coupled through a common resonator mode of the resonator to realize coupling between qubits necessary for a gate operation such as a controlled-NOT operation associated with the two or more qubits.

[0034]

With the method of the present invention, which realizes these features, it is possible to achieve a practical quantum computation capable of distinguishing and defining qubits through frequency regions regardless of

spatial positions of the qubits, requiring no wiring or fine patterning process, obtaining a high scale of integration and high scalability of qubits, and good coherency.

[0035]

In other words, by selecting qubits independent of a wiring and a fine pattering process, a high scale of integration of qubits can be achieved by a simple and practical method, which will be greatly beneficial to realizing a quantum computer superior to the present computers. To achieve the benefit, it is preferable to define and distinguish individual qubits by frequency regions not spatial positions. In this case, quantum-mechanical interaction may be effected to couple the qubits to one another. However, normally, the interaction naturally existing between the qubits stimulates phase relaxation, inhibiting generation of superposition state that is to be the major premise for the quantum information processing. As a result, an independent system which hardly interacts with the external world is used as a qubit. As a preferable method for introducing interaction between the independent qubits in a manner to be artificially controlled so as not to lose coherency, a resonator may be provided to couple each qubit with the common mode. The gate operation through coupling the qubits with the resonator modes requires three-level systems. The three-level systems enable gate operation independent of the influence of decoherence of natural emission using an adiabatic passage technique. In addition,

a qubit can be expressed by a superposing state of two levels whose transition is optically not allowed, and accordingly, decoherence hardly occurs and a quantum computation of a large number of processing steps is realized.

[0036]

In this way, practical quantum computation described above can be realized.

[0037]

Now, according to the method of the present invention, physical systems in a solid substance whose transition energies are inhomogeneously distributed can effectively be used as qubits as they are. In particular, a phase relaxation time of a nuclear spin of Pr^{3+} in oxide crystal obtained by dispersing rare-earth ions or particularly in a Y_2SiO_5 crystal having substantially no nuclear spin in the matrix crystal is relatively long, and thus it is known that the superposition state of two levels generated by hyperfine structure splitting caused by the nuclear spin can be retained for several tens of microseconds under light irradiation at approximately 4K that can be reached by use of liquid helium at atmospheric pressure (K. Ichimura, K. Yamamoto and N. Gemma, Phys. Rev., A58, 4116 (1998)). The time for which the superposition state can be retained is a peculiarly long time in the solid substance. A practical quantum computation is possible when the method of the present invention is applied to such a solid substance.

[0038]

Functions of the present invention will now be described in detail.

[0039]

In the present invention, a physical system having three energy levels is prepared. These energy levels are expressed by |0>, |1> and |e> in the order from the lowest energy level. In this case, it is assumed that |0>-|e> transition and |1>-|e> transition are optically allowed and |0>-|1> transition is substantially optically impossible. The above physical system is used as one qubit and information is expressed by lower two levels in the superposition state by the following expression (1):

$\alpha|0\rangle + \beta|1\rangle$ (α, and β are complex numbers) (1)

[0040]

In order to generate the above superposition state, light A having a frequency ν_A and light B having a frequency ν_B that respectively resonate with the transition frequency ν_{0e} of the |0>-|e> transition and the transition frequency ν_{1e} of the |1>-|e> transition are applied. The degree of interaction between the light and physical system is expressed by a quantum ν_{Rabi} called a Rabi frequency, which depends on the transition dipole moment μ and the electric field intensity E of the light and is expressed by the following equation (2):

[0041]

$\nu_{Rabi} \doteq \mu E/h$ (h is a Plank's constant) (2)

By irradiation of the light A and light B, levels |0> and |1> are superposed and the superposition state |PT> expressed by the following equation (3) is generated:

[0042]

$$|PT\rangle = (\nu_{Rabi,0e}{}^2 + \nu_{Rabi,1e}{}^2)^{-1/2} \cdot \nu_{Rabi,1e} \cdot |0\rangle - (\nu_{Rabi,0e}{}^2 + \nu_{Rabi,1e}{}^2)^{-1/2} \cdot \nu_{Rabi,0e} \cdot |1\rangle \quad (3)$$

where $\nu_{Rabi,0e}$ and $\nu_{Rabi,1e}$ are expressed by the following equations (4) and (5):

$$\nu_{Rabi,0e} = \mu_{0e} \cdot E_A/h \quad (4)$$

(where μ_{0e} is the transition dipole moment of the |0>-|e> transition, E_A is the electric field intensity of the light A).

$$\nu_{Rabi,1e} = \mu_{1e} \cdot E_B/h \quad (5)$$

(μ_{1e} is the transition dipole moment of the |1>-|e> transition, and E_B is the electric field intensity of the light B). |PT> is referred to as a population trapping state or dark state. As indicated by the equation (3), the ratio of the superposition of the two states can be controlled by the Rabi frequency and therefore by the light intensity. This state is shown in FIG. 1.

[0043]

|PT> is an eigenstate of Hamiltonian that expresses the interaction between the light A, light B and the physical system:

$$H = h \cdot \nu_{Rabi,0e} \cdot |e\rangle\langle 0| + h \cdot \nu_{Rabi,1e} \cdot |e\rangle\langle 1| + h.c.$$

(h.c: an Hermitian conjugate) (6)

In this state, even if a light separating state having

no change in intensity, i.e., light resonant with the transition from <0| or <1| to <e| is present, the transition to <e| does not occur.

[0044]

Now, suppose that a state is adiabatically changed from $\nu_{Rabi,0e} << \nu_{Rabi,1e}$ to $\nu_{Rabi,1e} << \nu_{Rabi,0e}$ by changing the intensities of light A and light B. The term "adiabatic" means that |PT> can be regarded as being always in the eigenstate while the intensities of the light A and light B are being changed. That is, the "eigenstate" |PT>(t) depending on time is expressed by the following equation (7) by use of the Rabi frequencies $\nu_{Rabi,0e}(t)$ and $\nu_{Rabi,1e}(t)$ depending on time:

$$|PT\rangle(t) = (\nu_{Rabi,0e}(t)^2 + \nu_{Rabi,1e}(t)^2)^{1/2} \cdot \nu_{Rabi,1e}(t) \cdot |0\rangle - (\nu_{Rabi,0e}(t)^2 + \nu_{Rabi,1e}(t)^2)^{1/2} \cdot \nu_{Rabi,0e}(t) \cdot |1\rangle \quad (7)$$

The physical system is not excited to the upper level |e> while the intensities of the light A and light B are being changed.

[0045]

As is clearly seen from the equation (7), the physical system that is initially in |PT>(t) = |0> is transferred to |PT>(t) = |1> after the change (FIG. 2). Further, since the excitation to the upper level |e> does not occur during the change, the process of the state change of the physical system is not disturbed by a random process of spontaneous

emission from $|e\rangle$. The rate of a change in light intensities that can maintain the adiabatic condition depends on the light intensities. That is, if the light intensities are enhanced, the "adiabatic" change of state is possible.

[0046]

In this way, the state of one qubit can be operated without disturbing the physical system. By this operation, a one-qubit gate operation can be performed.

[0047]

It is desirable that a plurality of physical systems are prepared to execute the quantum computation, and distinguished from one another and each physical system is individually operated as one qubit. In the following description, the qubits and physical systems corresponding thereto are considered, and distinguished from one another by use of a subscript i, expressing with $|0\rangle_i$, $|1\rangle_i$ and $|e\rangle_i$. For example, in a case where rare earth ions in a crystal are used for the quantum computation or quantum information processing, three energy levels of an i-th ion in the crystal are expressed as $|0\rangle_i$, $|1\rangle_i$ and $|e\rangle_i$.

[0048]

In the present invention, generally, physical systems having different transition frequencies are prepared to select an i-th physical system and perform the quantum gate operation. For example, in a case of the rare earth ions in the crystal, it is utilized that the transition frequencies of ions are distributed with a width called an inhomogeneous

width.

[0049]

Further, the transition frequencies of the $|0\rangle_i-|e\rangle_i$ transition, $|1\rangle_i-|e\rangle_i$ transition and $|0\rangle_i-|1\rangle_i$ transition of the i-th physical system are respectively expressed as $\nu_{0e,i}$, $\nu_{1e,i}$ and $\nu_{01,i}$. Light A and light B having the frequencies ν_A and ν_E are applied to a portion in which such physical systems are present. In this case, the physical system having the transition frequencies of $\nu_{0e,j} = \nu_A$ and $\nu_{1e,j} = \nu_E$ is influenced by the light and brought into the population trapping state, and thus the quantum gate operation can be effected. In practice, in a transition frequency space in which the transition frequencies ν_{0e}, ν_{1e} are taken, physical systems included in a certain range near (ν_A, ν_B) are influenced by the light and the gate operation can be effectively performed. The range is in the $\nu_{0e}-\nu_{1e}$ plane, along a straight line passing through a point (ν_A, ν_E) expressed by the following equation (8):

$$\nu_{1e} = \nu_{0e} + \nu_B - \nu_A \qquad (8)$$

In the area, the width is approximately $(\nu_{Rabi,0e}{}^2 + \nu_{Rabi,1e}{}^2)^{1/2}/2^{1/2}$ and the length is approximately a homogeneous width of the $|0\rangle-|e\rangle$ transition and the $|1\rangle-|e\rangle$ transition. The range will be illustrated in FIG. 3.

[0050]

If one physical system is contained in the area, one qubit is expressed by one physical system. Further, if

physical systems are contained in the area, one qubit is expressed by the quantum state of one group of the whole physical systems.

[0051]

Therefore, if the physical systems distributed in the $\nu_{0e}-\nu_{1e}$ plane are divided into groups having approximately the size of the area shown in FIG. 3 and each of the groups is used as a qubit, a qubit to be operated can be selected according to the frequency of irradiated light.

[0052]

In order to perform the quantum information processing, particularly, the quantum computation by use of the qubits, it is necessary to quantum-mechanically couple the qubits and to perform the gate operation between the two qubits. In the present invention, coupling between the qubits is realized by arranging the physical systems in an optical resonator. The mechanism is explained below.

[0053]

The physical systems in the resonator interact with the resonator. First, the interaction between one physical system and the resonator is considered. If the physical system has levels of allowed dipole transition, the interaction Hamiltonian between the transition dipole moment and the resonator mode resonant with the moment is expressed by the following equation (9):

$$H = h/(2\pi)\cdot g\cdot c^{+}|1\rangle\langle e| + h/(2\pi)\cdot g\cdot c|e\rangle\langle 1| \qquad (9)$$

In this case, it is assumed that the dipole transition

that interacts with the resonator mode is the <1|-<e| transition. In the equation (9), c^+ and c are respectively creation and annihilation operators of the resonator mode. Further, g is a coupling constant between the resonator mode and the physical system, which is expressed by the following equation (10).

[0054]

$$g = -(2\pi)(\mu \cdot e \cdot E_C)/h \qquad (10)$$

where μ is a transition dipole moment vector and e is a polarization vector of the resonator mode. E_C is amplitude of a vacuum field of the given mode, which is expressed by the following equation (11).

[0055]

$$E_C = (h \cdot \nu_{cavity}/(2\varepsilon_0 \cdot V))^{1/2} \qquad (11)$$

where ν_{cavity} is the frequency of the mode, ε_0 is the dielectric constant of vacuum and V is the volume of the resonator.

[0056]

Next, a case where two physical systems are contained in the resonator is considered.

[0057]

It is assumed that respective transitions $\nu_{1e,1}$ and $\nu_{1e,2}$ of the two transitions in each of the two physical systems resonate with the resonator mode. The physical systems are irradiated with light 1 and light 2 that respectively resonate with the remaining transitions, that is, $\nu_{0e,1}$ and $\nu_{0e,2}$. FIG. 4 schematically shows the state.

[0058]

At this time, Hamiltonian is expressed by the following equation (12):

[0059]

[MATH 1]

$$H = \sum_{i=1}^{2} \left(h \cdot \nu_{Rabi,i} \cdot |0\rangle_{ii} \langle e| + h.c. + (h/(2\pi)) \cdot g \cdot c^{+} |1\rangle_{ii} \langle c| + h.c. \right) \qquad (12)$$

[0060]

In this case, if a difference between the physical systems with respect to the dipole moments of the |0>-|e> transition and |1>-|e> transition can be neglected, $\nu_{Rabi,i}$ is expressed by the following equation (13):

$$\nu_{Rabi,i} = \mu_{0e} \cdot E_i / h \qquad (13)$$

(where μ_{0e} is the transition dipole moment of the |0>-|e> transition and E_i is the electric field intensity of the light i).

[0061]

Also, in this case, like the case where two-wavelength light beams are applied to a single qubit, the "population trapping state" that is not excited to the upper level $|e\rangle_i$ is present as the eigenstate of the equation (12). It is known that two eigenstates among them are expressed by the following equations (14) and (15).

[0062]

$$|PT_0\rangle = |1\rangle_1 |1\rangle_2 |n=0\rangle \qquad (14)$$

$$|PT_1\rangle = N_1(\nu_{Rabi,2} \cdot g \cdot |0\rangle_1|1\rangle_2|n=0\rangle + \nu_{Rabi,1} \cdot g \cdot |1\rangle_1|0\rangle_2|n=0\rangle - (2\pi) \cdot \nu_{Rabi,1} \cdot \nu_{Rabi,2} \cdot |1\rangle_1|1\rangle_2|n=1\rangle) \quad (15)$$

where N_1 is a normalization constant. Further, the third ket, for example, ($|n=0\rangle$) indicates the quantum state of the resonator mode that has a quantum number good for the number of photons.

[0063]

A controlled-NOT operation, which is a two-qubit gate operation, can be effected by use of the "population trapping state". As one method of the controlled-NOT operation, a method proposed by Pellizzari et al. (T. Pellizzari, S. A. Gardiner, J. I. Cirac and P. Zoller, Phys. Rev. Lett. 75, 3788 (1995)) can be utilized. In this method, a series of single ions arranged in the ion trap are coupled through the resonator mode and spatially converged laser beams distinguish the individual ions and operate them, thereby performing a quantum computing. Next, the manner how the controlled-NOT operation is performed is explained by applying the above method proposed by Pellizzari et al.

[0064]

In the method of Pellizzari et al., degenerated levels as $|0\rangle$, $|1\rangle$ and $|e\rangle$ are used for the controlled-NOT operation. In the following description, it is assumed that $|0\rangle$, $|1\rangle$ and $|e\rangle$ are levels in which $|0\rangle$ and $|0'\rangle$, $|1\rangle$ and $|1'\rangle$, and $|e\rangle$ and $|e'\rangle$ are respectively degenerated. In the

actual physical system, for example, it is utilized that levels generated by hyperfine structure splitting of rare earth ions in the crystal are degenerated. Like the case of adiabatic passage of the single qubit, suppose a case where the Rabi frequency condition is changed from $\nu_{Rabi,1} << \nu_{Rabi,2}$ to $\nu_{Rabi,2} << \nu_{Rabi,1}$ by controlling the laser beam intensities applied to the two qubits. In this case, the "population trapping state" expressed by the equation (15) is changed as indicated by the following expressions (16) and (17):

$$|PT_1\rangle = |0\rangle_1|1\rangle_2|n=0\rangle \rightarrow |1\rangle_1|0\rangle_2|n=0\rangle \qquad (16)$$

$$|0'\rangle_1|1'\rangle_2|n=0\rangle \rightarrow |1'\rangle_1|0'\rangle_2|n=0\rangle \qquad (17)$$

The operation has a function of exchanging the states of the physical system 1 and the physical system 2.

[0065]

So far, a case where only two physical systems are present has been considered. The above method can also be applied in a case where physical systems coupled through the common resonator mode are considered, attention is paid to the k-th and l-th physical systems, laser beams resonant with $\nu_{0e,k}$ and $\nu_{0e,l}$ are selectively affected thereto, and the condition is changed from $\nu_{Rabi,k} << \nu_{Rabi,l}$ to $\nu_{Rabi,l} << \nu_{Rabi,k}$. In this case also, the similar exchanging operation expressed by the following expressions (18) and (19) can be effected between the k-th and l-th physical systems.

[0066]

$$|PT_1\rangle = |0\rangle_k|1\rangle_l|n=0\rangle \rightarrow |1\rangle_k|0\rangle_l|n=0\rangle \quad (18)$$

$$|0'\rangle_k|1'\rangle_l|n=0\rangle \rightarrow |1'\rangle_k|0'\rangle_l|n=0\rangle \quad (19)$$

In order to effect the controlled-NOT operation between the k-th and l-th qubits, the quantum states expressing the information "0" and information "1" are re-defined in the physical systems which carry the respective qubits. That is, the quantum states $|0(new)\rangle_k$, $|1(new)\rangle_k$, $|0(new)\rangle_l$ and $|1(new)\rangle_l$ that newly express "0" and "1" are defined by the following equations (20) to (23).

$$|0(new)\rangle_k = |0\rangle_k \quad (20)$$

$$|1(new)\rangle_k = |1\rangle_k \quad (21)$$

$$|0(new)\rangle_l = |1\rangle_l \quad (22)$$

$$|1(new)\rangle_l = |1'\rangle_l \quad (23)$$

[0067]

As a result, if laser beams of $\nu_{0e,k}$ and $\nu_{0e,l}$ are applied and the condition is changed from $\nu_{Rabi,k} \ll \nu_{Rabi,l}$ to $\nu_{Rabi,l} \ll \nu_{Rabi,k}$, the four quantum states of $|0(new)\rangle_k|0(new)\rangle_l$, $|0(new)\rangle_k|1(new)\rangle_l$, $|1(new)\rangle_k|0(new)\rangle_l$ and $|1(new)\rangle_k|1(new)\rangle_l$ are transformed as indicated by the following equations (24) to (27).

[0068]

$$|0(new)\rangle_k|0(new)\rangle_l = |0\rangle_k|1\rangle_l \rightarrow |1\rangle_k|0\rangle_l \quad (24)$$

$$|0(new)\rangle_k|1(new)\rangle_l = |0\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|0'\rangle_l \quad (25)$$

$$|1(new)\rangle_k|0(new)\rangle_l = |1\rangle_k|1\rangle_l \rightarrow |1\rangle_k|1\rangle_l \quad (26)$$

$$|1(new)\rangle_k|1(new)\rangle_l = |1\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|1'\rangle_l \quad (27)$$

Next, $|1\rangle_l$ and $|1'\rangle_l$ of the l-th physical system are

exchanged with each other by irradiating laser beams while applying an external field:

$$|1\rangle_l \rightarrow |1'\rangle_l \quad (28)$$

$$|1'\rangle_l \rightarrow |1\rangle_l \quad (29)$$

Finally, the states of the k-th and l-th physical systems are exchanged with each other by making a change from $\nu_{Rabi,l} << \nu_{Rabi,k}$ to $\nu_{Rabi,k} << \nu_{Rabi,l}$ in a reverse direction with respect to the first operation by controlling the intensities of two kinds of laser beam.

[0069]

The above series of operations can be summarized as indicated by the following equations (24) to (27).

[0070]

$$|0(new)\rangle_k|0(new)\rangle_l = |0\rangle_k|1\rangle_l \rightarrow |1\rangle_k|0\rangle_l \rightarrow |1\rangle_k|0\rangle_l \rightarrow |0\rangle_k|1\rangle_l = |0(new)\rangle_k|0(new)\rangle_l \quad (24)$$

$$|0(new)\rangle_k|1(new)\rangle_l = |0\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|0'\rangle_l \rightarrow |1\rangle_k|0'\rangle_l \rightarrow |0\rangle_k|1'\rangle_l = |0(new)\rangle_k|1(new)\rangle_l \quad (25)$$

$$|1(new)\rangle_k|0(new)\rangle_l = |1\rangle_k|1\rangle_l \rightarrow |1\rangle_k|1\rangle_l \rightarrow |1\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|1'\rangle_l = |1(new)\rangle_k|1(new)\rangle_l \quad (26)$$

$$|1(new)\rangle_k|1(new)\rangle_l = |1\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|1'\rangle_l \rightarrow |1\rangle_k|1\rangle_l \rightarrow |1\rangle_k|1\rangle_l = |1(new)\rangle_k|0(new)\rangle_l \quad (27)$$

Meanwhile, the controlled-NOT operation is an operation in which if the state of a given bit (control bit) is "0" then another given bit (target bit) is remained as it is, and if the state of the control bit is "1" then the target bit is inverted. The controlled-NOT operation is expressed as follows if the control bit is indicated on the left side and

the target bit is indicated on the right side.

[0071]

$$
\begin{aligned}
&|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle \\
&|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle \\
&|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle \\
&|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle \qquad (28)
\end{aligned}
$$

Accordingly, using the k-th qubit as a control bit and the l-th qubit as a target bit, the controlled-NOT operation can be performed by controlling the laser beam.

[0072]

The quantum information processing operation involving the computation can be effected by combining the above controlled-NOT operation and the one-qubit gate operation.

[0073]

As described above, according to the present invention, the quantum information processing operation can be effected by selecting qubits by selecting a laser beam wavelength and effecting the one-qubit and two-qubit gate operations without requiring special wiring and fine process.

[0074]

[Embodiments]

Explanation of the embodiments of the present invention will now be made with reference to accompanying drawings.

[0075]

(Embodiment 1)

To execute quantum information processing related to an embodiment of the invention, a Y_2SiO_5 crystal of

2 mm × 2 mm × 2 mm in which 0.05% of Pr^{3+} ions are dispersed (which is obtained by replacing 0.05% of Y^{3+} of Y_2SiO_5 by Pr^{3+}) was prepared. The crystal was placed in a cryostat and the temperature was kept at 4.2K. Further, a resonator was provided outside the cryostat. The laser beam A from the ring-dye laser whose frequency was set to ν_A near 605.98 nm (16502.3 cm^{-1}) that resonates with the transition between the lowest stark $^3H_4(1)$ level and the $^1D_2(1)$ electron excitation level of Pr^{3+} in the crystal was prepared. In addition, laser beam B having a frequency of $\nu_E = \nu_A - 17.3$ MHz generated by the acoustooptic device through the laser beam was prepared.

[0076]

First, the laser beam A with the intensity of 50 mW/cm^2 and the laser beam B with the intensity of 5 W/cm^2 were applied to the crystal for 0.1 second or more, and immediately after this, only the laser beam A with the intensity of 5 mW/cm^2 was applied to the crystal for 1 μs, and then the emission intensity was measured. Next, the laser beam A with the intensity of 50 mW/cm^2 and the laser beam B with the intensity of 5 W/cm^2 were applied to the crystal for 0.1 second or more again, and immediately after this, only the laser beam B with the intensity of 5 mW/cm^2 was applied to the crystal for 1 μs, and then the emission intensity was measured. As the result of this, the ratio of the first measured value of the emission intensity to the second measured value was approximately 3:1. This is because

a part of the ions in a region simultaneously resonant with the light A and light B were brought into the following superposition state of the lower two levels |a> and |b> of $^3H_4(1)$ in accordance with the Rabi frequencies $\nu_{Rabi,A}$ and $\nu_{Rabi,B}$ associated with the light A and light B:

$$(\nu_{Rabi,A}^2 + \nu_{Rabi,B}^2)^{-1/2} \cdot \nu_{Rabi,B'}|a\rangle$$

$$- (\nu_{Rabi,A}^2 + \nu_{Rabi,B}^2)^{-1/2} \cdot \nu_{Rabi,A'}|b\rangle$$

Further, it is considered that most part of the ions that are not in the superposition state are transferred to the hyperfine structure levels that do not relate to the superposition state.

[0077]

(Embodiment 2)

Using the processor of FIG. 5, quantum computation according to an embodiment of the invention was performed.

[0078]

In respect to FIG. 5, a sample 11 is held in a cryostat (not shown). The sample 11 is sandwiched between coils for applying a magnetic field. A resonator 13 and a photodetector 14 surround the cryostat. The sample 11 is irradiated with a laser beam 15 from an external ring-dye laser (not shown).

[0079]

To perform quantum computation according to one embodiment of the invention, a Y_2SiO_5 crystal 11 of 2 mm × 2 mm × 2 mm in which 0.05% of Pr^{3+} ions were dispersed was prepared. The crystal 11 was placed in the

cryostat, and the temperature was kept at 4.2K. First, the wavelength of the laser beam from the ring-dye laser was set near 605.98 nm (16502.3 cm^{-1}) that resonates with the transition between the lowest stark $^3H_4(1)$ level and the $^1D_2(1)$ electron excitation level of Pr^{3+} in the crystal 11, and then the fluorescence excitation spectrum emitted from the sample 11 was measured by means of the photodetector 14. As a result, a depression due to decrease in absorption was observed in the spectrum over a frequency range of approximately 100 kHz (FIG. 6). This is because a part of ions concerned in absorption are subjected to population trapping due to the resonator mode and laser beam and therefore the number of ions to be excited is reduced.

[0080]

Next, a static magnetic field was applied to the sample 11, and the degeneracy of each level split into the levels of the hyperfine structure was broken by 5MHz. Subsequently, applying two vibrating magnetic fields having a frequency lower than that of the split of one of the splits of hyperfine structure of the stark level $^3H_4(1)$, 10.2 MHz and 17.3 MHz by 5 MHz, the degeneracy was split. Of the level generated by the split, the state was transferred to the lower energy level. Next, the application of the magnetic field was broken. A laser beam k whose frequency was fixed at ν_k near the wave number of 16502.3 cm^{-1} and a laser beam k' whose frequency was lower than that of the former laser beam by 17.3 MHz were radiated on condition that

the intensity (5 W/cm^2) of the laser beam k' was set to 100 times the intensity of the laser beam k, thereby transferring the state to the lower level of the hyperfine structure levels apart by 17.3 MHz in frequency. This state was called $|0>_k$. Also, the higher level was called $|1>_k$. Next, in the same manner, with light radiation whose frequency ($\nu_k = \nu_k + 100$ MHz) was apart by 100 MHz from the frequency ν_k and application of vibrating magnetic field, the state was transferred to the higher energy of energies generated by breaking the degeneracy of ion resonating with the laser beam 1 having the frequency of ν_1, and further transferred to the higher level of the hyperfine structure levels apart by 17. 3 MHz in frequency, and finally the magnetic field was broken. This transferred end state was called $|0>_1$. The state corresponding to the lower level of the energy generated by breading the degeneracy and corresponding to the higher level of the energy of the hyperfine structure levels apart by 17.3 MHz in frequency was called $|1>_1$.

[0081]

An initial state was prepared in this manner. First, the intensity I_k of the laser beam k and the intensity I_1 of the laser beam 1 was set so as to be $I_k<<I_1$, and then changed so as to be $I_1<<I_k$ after approximately 1 μs. The state is illustrated in FIG. 7. Subsequently, with application of a static magnetic field and a vibrating magnetic field and radiation of laser beams, the degeneracy of the higher energy

level of two levels apart by 17.3 MHz in frequency was broken, and thus generated quantum state of the two levels was exchanged with each other. Further, the laser beam 1 and laser beam k were radiated again, but this time, they were set so as to be $I_1 \ll I_k$, and changed so as to be $I_k \ll I_1$ after approximately 1 μs.

[0082]

Finally, with application of a static magnetic field and a vibrating magnetic field, and radiation of laser beams having a frequency of ν_1, observation was made to find in which one of levels where the degeneracy was broken in the static magnetic field, an ion resonating with the light 1 was present. It was found that an ion was present in $|0\rangle_1$, that is, in the higher energy level.

[0083]

Next, a magnetic field was applied to the sample 11 again, and the degeneracy of each level split into the levels of the hyperfine structure was broken by 5 MHz. Subsequently, applying two vibrating magnetic fields having a frequency lower than that of the split of hyperfine structure of the stark level $^3H_4(1)$, and splits of 10.2 MHz and 17.3 MHz by 5 MHz, the degeneracy was split. Of the level generated by the split, the state was transferred to the lower energy level. Next, the application of the magnetic field was broken. A laser beam k whose frequency was fixed at ν_k near the wave number of 16502.3 cm^{-1} and a laser beam k' whose frequency was lower than that of

the former laser beam by 17.3 MHz were radiated on condition that the intensity (5 W/cm^2) of the laser beam k' was set to 100 times the intensity of the laser beam k, thereby transferring the state to the lower level $|0>_k$ of the hyperfine structure levels apart by 17.3 MHz in frequency. Next, in the same manner, with light radiation whose frequency ($\nu_k = \nu_k$ + 100 MHz) was apart by 100 MHz from the frequency ν_k and application of vibrating magnetic field, the state was transferred to the lower energy of energies generated by breaking the degeneracy of ion resonating with the laser beam 1 having the frequency of ν_1, and further transferred to the higher level of the hyperfine structure levels apart by 17.3 MHz in frequency, i.e., $|1>_1$.

[0084]

In this state, first, the intensity I_k of the laser beam k and the intensity I_1 of the laser beam 1 was set so as to be $I_k<<I_1$, and then changed so as to be $I_1<<I_k$ after approximately 1 μs. Subsequently, with application of a static magnetic field and a vibrating magnetic field and radiation of laser beams, the degeneracy of the higher energy level of two levels apart by 17.3 MHz in frequency was broken, and thus generated quantum state of the two levels was exchanged with each other. Further, the laser beam 1 and laser beam k were radiated again, but this time, they were set so as to be $I_1<<I_k$, and changed so as to be $I_k<<I_1$ after approximately 1 μs.

[0085]

Finally, with application of a static magnetic field and a vibrating magnetic field, and radiation of laser beams having a frequency of ν_1, observation was made to find in which one of levels where the degeneracy was broken in the static magnetic field, an ion resonating with the light 1 was present. It was found that the ion was present in the level of lower energy, that is, in $|1\rangle_1$.

[0086]

In the same manner, before starting an operation using two kinds of laser beam, an initial state was set such that the state of an ion interacting with the light k is $|1\rangle_k$, and the state of an ion interacting with the light 1 is $|0\rangle_1$. After the series of operations using the two kinds of laser beam described above, the state of the ion interacting with the light 1 was finally observed, and the state was found to be $|1\rangle_1$.

[0087]

Finally, an initial state before starting an operation using two kinds of laser beam was set such that the state of an ion interacting with the light k is $|1\rangle_k$, and the state of an ion interacting with the light 1 is $|1\rangle_1$. After the series of operations with the radiation of laser beams, similar to the above, the state of the ion interacting with the light 1 was finally observed, and the state was found to be $|0\rangle_1$.

[0088]

In each case, the state of the ion interacting with the light k before and after the series of operations using the two laser beams was observed. The state resulted unchanged.

[0089]

As described above, when the initial state is $|0\rangle_k|0\rangle_l$, the final state is $|0\rangle_k|0\rangle_l$, when the initial state is $|0\rangle_k|1\rangle_l$, the final state is $|0\rangle_k|1\rangle_l$, when the initial state is $|1\rangle_k|0\rangle_l$, the final state is $|1\rangle_k|1\rangle_l$, when the initial state is $|1\rangle_k|1\rangle_l$, the final state is $|1\rangle_k|0\rangle_l$, and thus the controlled-NOT operation can be realized.

[0090]

(Embodiment 3)

In the embodiment 2, a crystal 11 containing Pr^{3+} was formed into a thin plate of 2 mm × 22 mm × 0.5 mm and multi-layered coatings were applied to opposite surfaces thereof to form a resonator. The multi-layered coatings were dielectric mult-layered films and formed to realize a high reflectance in a narrow bandwidth around ν_A (near 605.98 nm). The resonator 13 provided outside the cryostat was omitted, and then the fluorescence excitation spectrum was measured like the embodiment 2. As a result, a depression considered to have been caused by decrease in absorption appeared over a frequency range of approximately 100 kHz. In this case, reduction in the fluorescence intensity was several ten times that in a case where the resonator 13 was provided outside the cryostat. It is

considered that this is because the volume of the resonator was reduced and the coefficient of coupling with the resonator mode was increased. Also, in this case, the controlled-NOT operation same as in the embodiment 2 was realized.

[0091]

(Embodiment 4)

Using the processor illustrated in FIG. 8, a quantum computation according to the present invention was executed. The quantum computer of FIG. 8 is provided with a cryostat 10 as a cooling means and an argon ion laser pumped ring-dye laser 20. A pulse light from the laser 20 is introduced into the cryostat 10 by an optical path 23 via an acoustooptic device 21 and an electrooptic device 22. A resonator 13 is provided in the cryostat 10. A sample 11 and two coils 12 for applying a magnetic field to the sample 11 is arranged in the resonator 13. The coils 12 are connected to a pulse high frequency magnetic field driver 15 and static magnetic field applying power supply 16 outside the cryostat 10. A photodetector 14 for detecting transmitting lights of the laser beam irradiated on the sample 11 or light emission from the sample is provided outside the cryostat 10.

[0092]

In the case of this processor, data input, performance of gate operation and readout of the result were performed using a pulse train generated by interacting the electrooptic device 22 with light on which the wavelength was controlled

by the acoustooptic device 21. The electrooptic device 22 was controlled with an electric signal generated through input data, a gate operation program and readout operation information. At the same time, a magnetic field caused by the coil 12 controlled by the electric signal was also used. Pr^{3+} in the resonator 13 cooled at 4K in the cryostat was irradiated with a pulse train, and the magnetic field was synchronously applied to the Pr^{3+}. Further, a light emission from the crystal 11 was detected by the photodetector 14.

[0093]

A light from the argon ion laser pumped ring-dye laser 20 was divided into a number of branches; the acoustooptic device 21 and electrooptic device 22 were provided in respective branches; and the respective wavelengths were expressed by a light pulse train resonating with a plurality of qubits that were defined by a frequency space. As a result, a quantum operation using three or more qubits could be performed.

[0094]

[Advantage of the Invention]

As has been described above, the present invention can realize the effects to be descried below:

(1) Physical systems each having three levels are used as qubits and, when the qubits are operated by use of light, a technique called adiabatic passage is used utilizing population trapping induced where two-wavelength light beams are applied to the three-level systems. (2) A plurality of

physical systems having different transition frequencies between the levels are used as qubits, and in operation of qubits by use of light, individual qubits can independently be operated by resonating a light angular frequency with the transition frequency of a desired qubit. (3) Transitions of the respective qubits are coupled through a common resonator mode of the resonator to realize coupling between cubits necessary for a gate operation such as a controlled-NOT operation associated with the two or more qubits.

[0095]

As a result, it is possible to achieve a practical quantum computation capable of distinguishing and defining qubits by frequency regions regardless of spatial positions of the qubits, requiring no wiring or fine patterning process, obtaining a high scale of integration and high scalability of qubits, and good coherency.

[Brief description of the Drawings]

[FIG. 1] A view showing an example of a condition where population trapping occurs when a three-level system is irradiated with two kinds of light according to the present invention.

[FIG. 2] A diagram for illustrating a condition where adiabatic passage occurs by irradiation of two-wavelength light beams according to the present invention.

[FIG. 3] A diagram showing an example of a region in the transition frequency plane that causes population trapping by the interaction with the two-wavelength light

beams according to the present invention.

[FIG. 4] A view showing a resonator mode acting on two physical systems and two laser beams according to the present invention.

[FIG. 5] A conceptual view showing an example of a principal portion of a quantum information processor used in the embodiments of the present invention.

[FIG. 6] A diagram showing an example of fluorescence excitation spectrum of $Pr^{3+}:Y_2SiO_5$ in a resonator in an embodiment of the present invention.

[FIG. 7] A diagram showing an example of changes in intensity with time of two-wavelength light beams used in the gate operation in the embodiment of the present invention.

[FIG. 8] A block diagram of a quantum computer according to the embodiment of the present invention.

[Explanation of Reference Symbols]

10: Cryostat

11: Sample

12: Coil

13: Resonator

14: Photodetector

15: Pulse high frequency magnetic field driver

16: Static magnetic field applying power supply

20: Ring-dye laser

21: Acoustooptic device

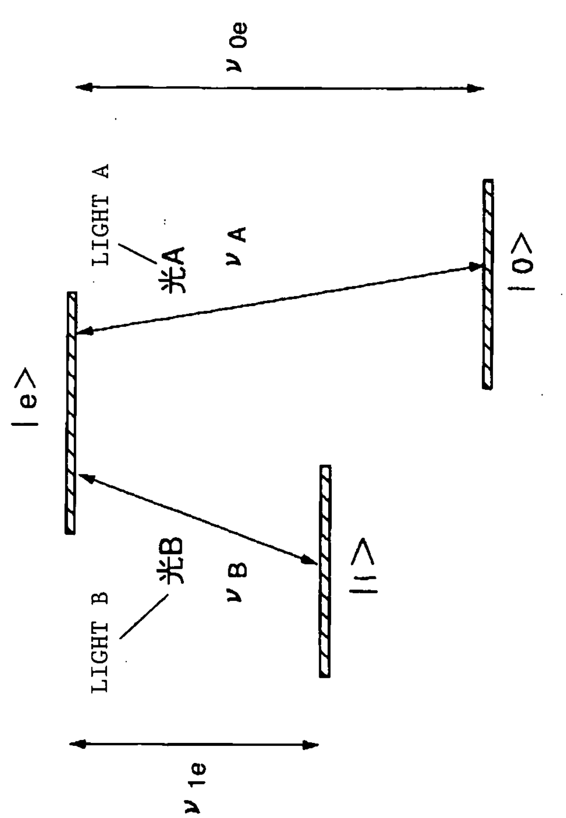
22: Electrooptic device

23: Optical path

[NAME OF DOCUMENT]

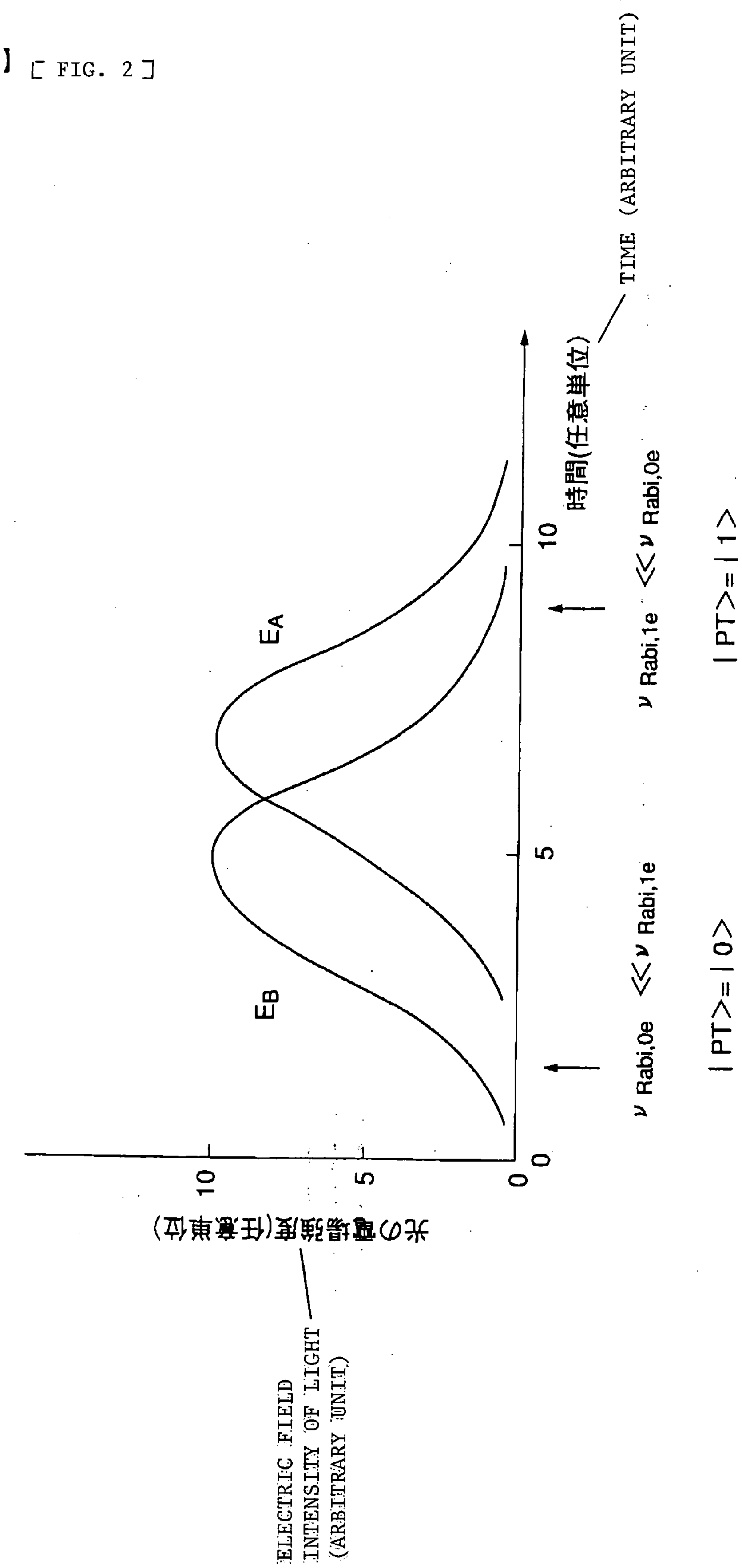
【書類名】　　　　　図面　DRAWINGS

【図1】 [FIG. 1]



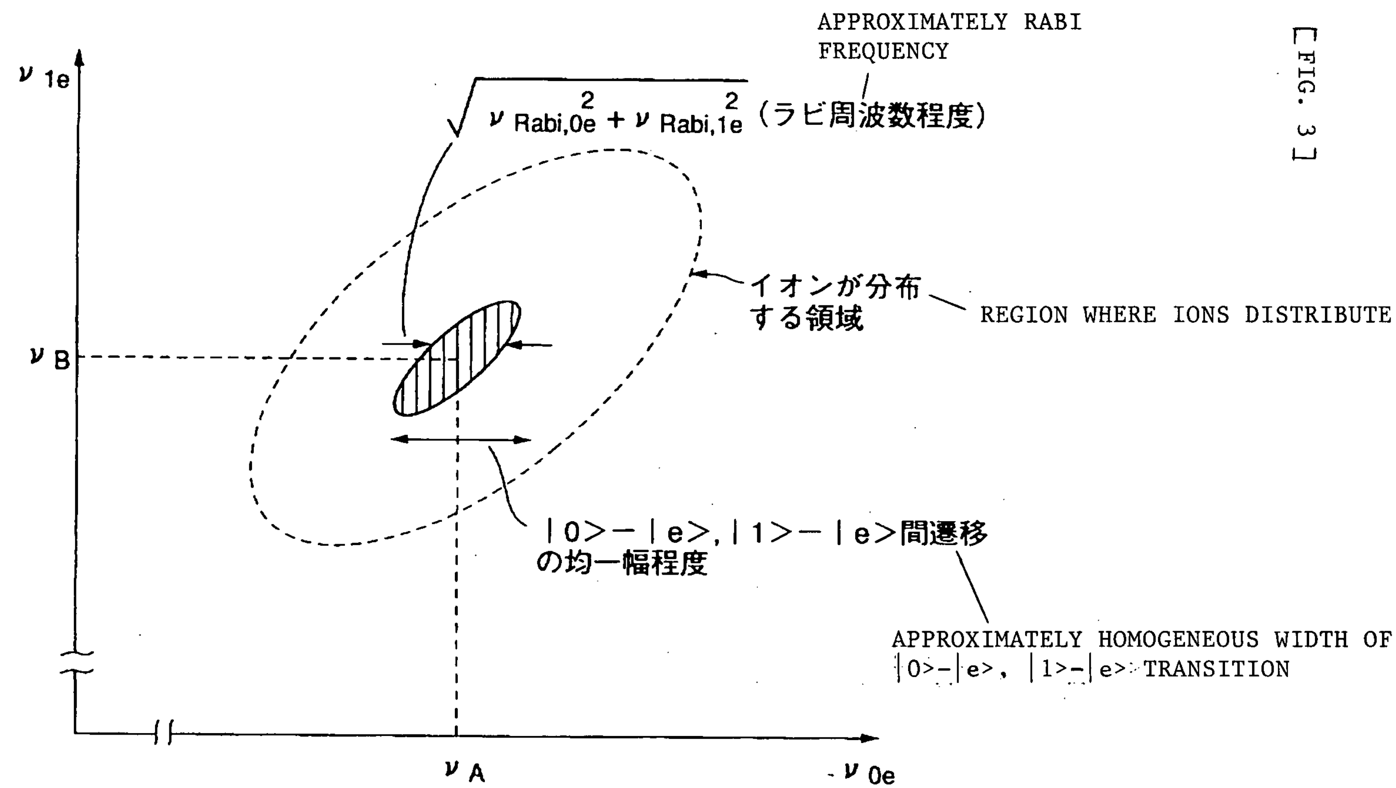
$$|PT\rangle = \frac{\nu_{Rabi,1e}}{\sqrt{\nu_{Rabi,0e}^2 + \nu_{Rabi,1e}^2}} \cdot |0\rangle - \frac{\nu_{Rabi,0e}}{\sqrt{\nu_{Rabi,0e}^2 + \nu_{Rabi,1e}^2}} \cdot |1\rangle$$

【図２】 [FIG. 2]



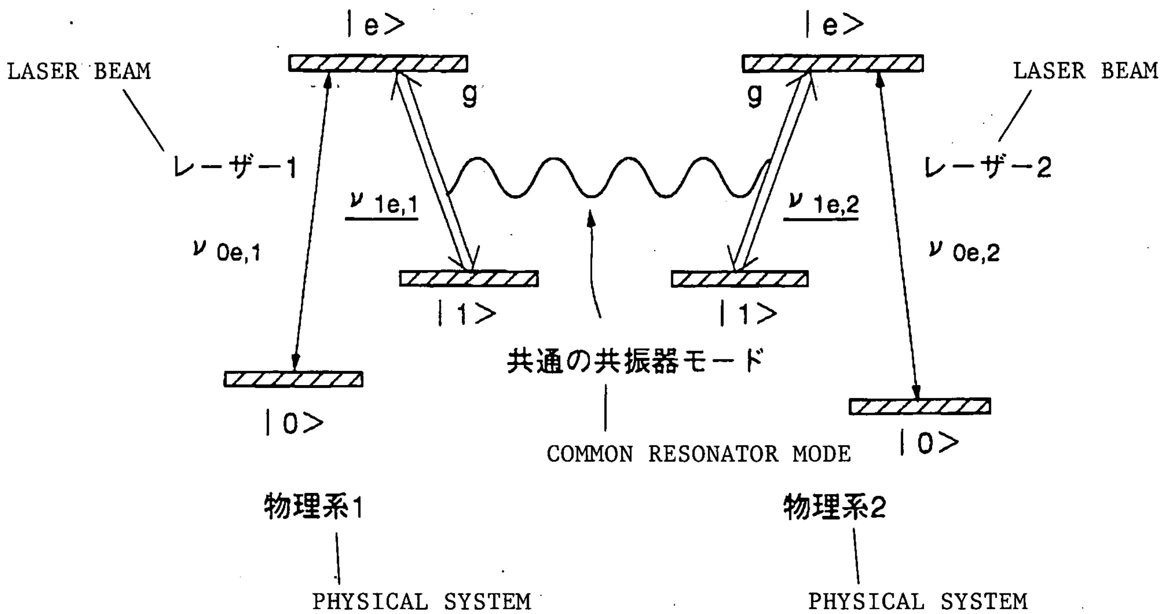
時間(任意単位)
TIME (ARBITRARY UNIT)
光の電場強度(任意単位)
ELECTRIC FIELD INTENSITY OF LIGHT (ARBITRARY UNIT)
E_A
E_B
0
5
10
ν Rabi,0e ≪ ν Rabi,1e
ν Rabi,1e ≪ ν Rabi,0e
|PT>=|0>
|PT>=|1>

【図3】 [FIG. 3]



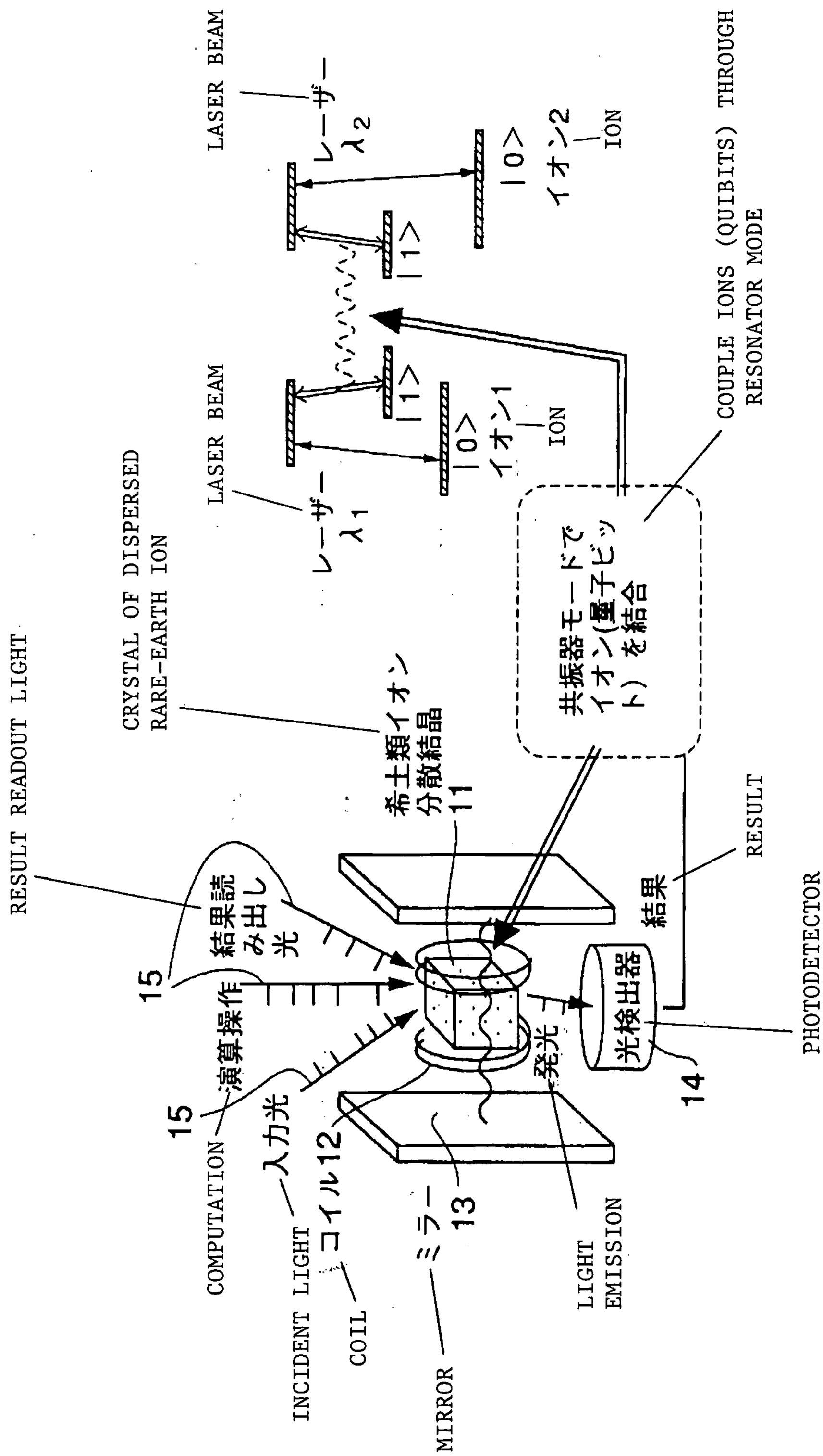
APPROXIMATELY RABI FREQUENCY
$\sqrt{\nu_{Rabi,0e}^2 + \nu_{Rabi,1e}^2}$ (ラビ周波数程度)
イオンが分布する領域
REGION WHERE IONS DISTRIBUTE
|0>−|e>, |1>−|e>間遷移の均一幅程度
APPROXIMATELY HOMOGENEOUS WIDTH OF |0>−|e>, |1>−|e> TRANSITION
ν_{1e}
ν_B
ν_A
ν_{0e}

【図4】 [FIG. 4]



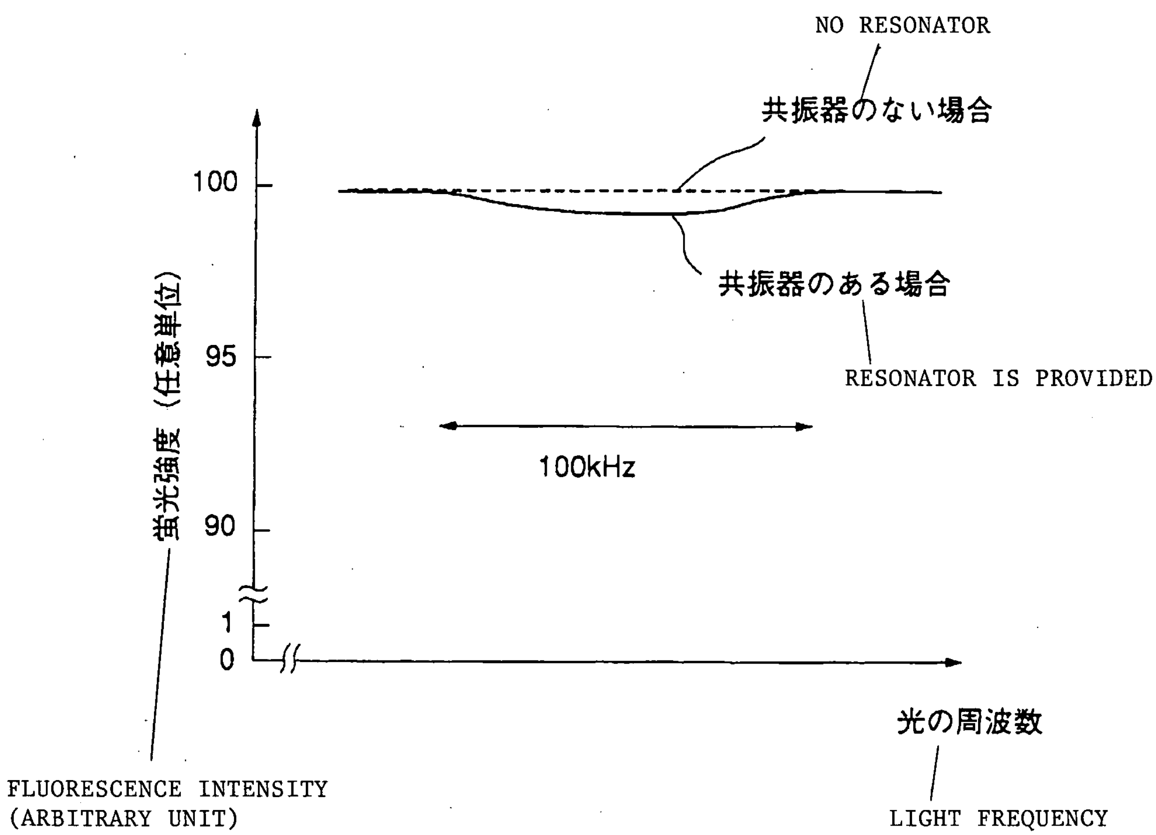
|e>
|e>
LASER BEAM
LASER BEAM
g
g
レーザー1
レーザー2
ν 1e,1
ν 1e,2
ν 0e,1
ν 0e,2
|1>
|1>
共通の共振器モード
COMMON RESONATOR MODE
|0>
|0>
物理系1
物理系2
PHYSICAL SYSTEM
PHYSICAL SYSTEM

【図5】 [FIG. 5]



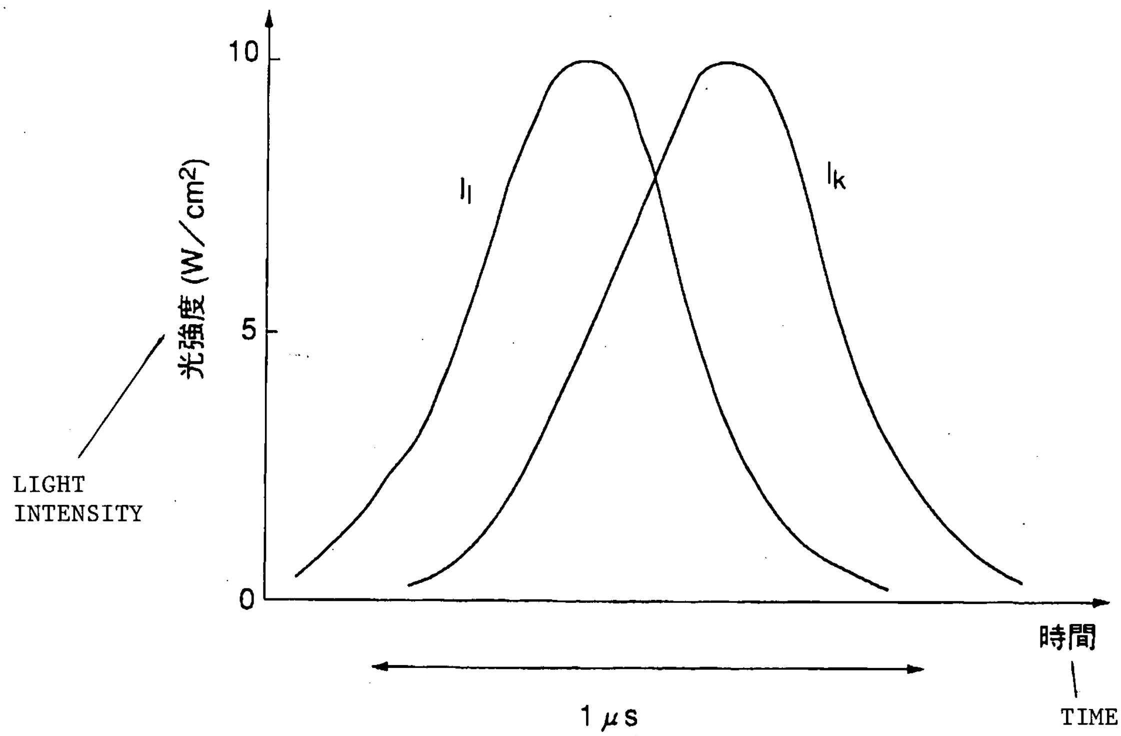
RESULT READOUT LIGHT
CRYSTAL OF DISPERSED RARE-EARTH ION
LASER BEAM
LASER BEAM
COUPLE IONS (QUIBITS) THROUGH RESONATOR MODE
レーザー λ_1
レーザー λ_2
|1>
|0>
イオン1
ION
|1>
|0>
イオン2
ION
共振器モードでイオン(量子ビット)を結合
希土類イオン分散結晶
11
結果読み出し光
15
演算操作
15
入力光
コイル12
ミラー
13
発光
結果
RESULT
光検出器
14
PHOTODETECTOR
COMPUTATION
INCIDENT LIGHT
COIL
MIRROR
LIGHT EMISSION

【図6】 [FIG. 6]

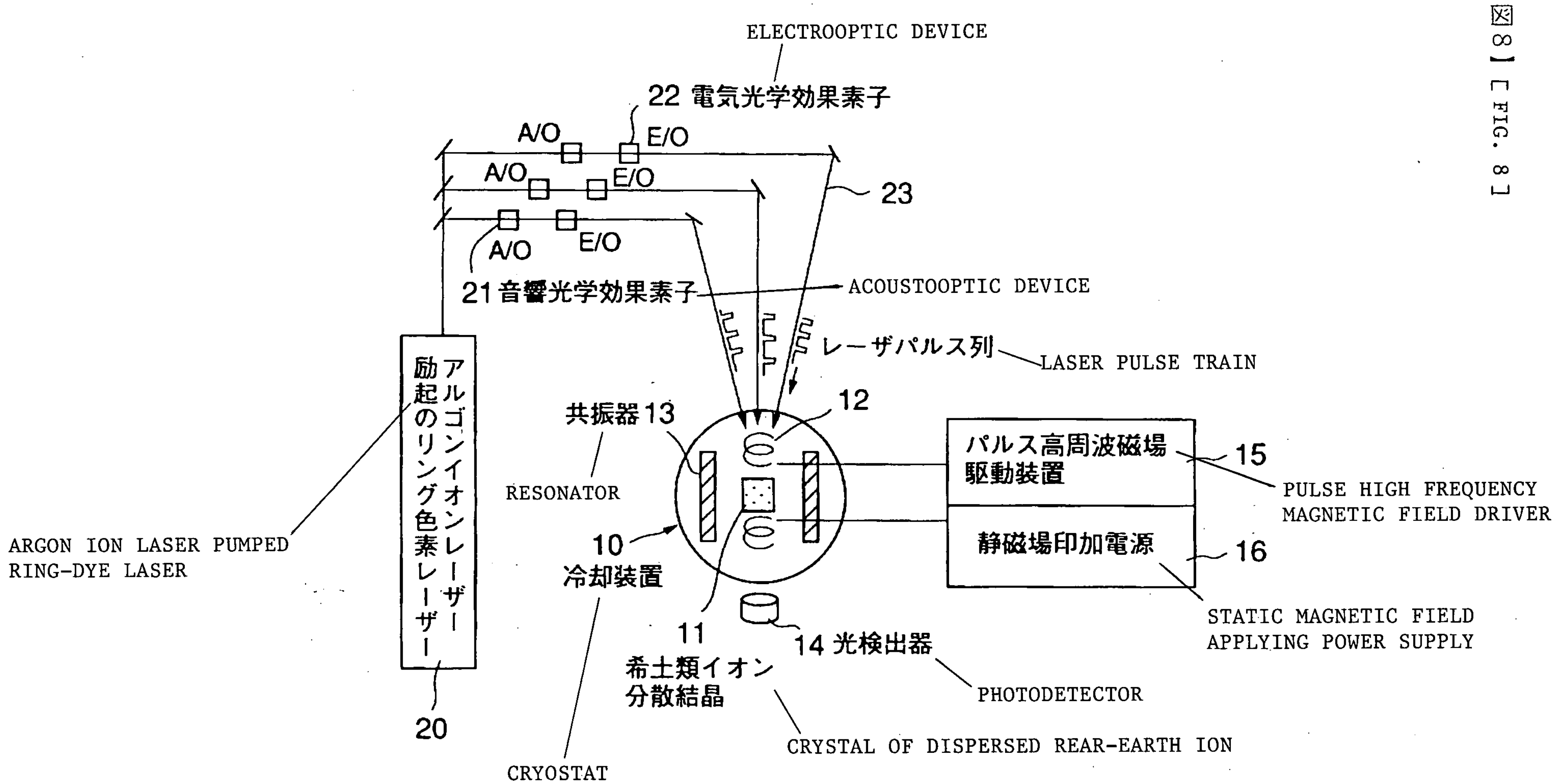


NO RESONATOR
共振器のない場合
100
95
90
1
0
共振器のある場合
RESONATOR IS PROVIDED
100kHz
蛍光強度（任意単位）
FLUORESCENCE INTENSITY
(ARBITRARY UNIT)
光の周波数
LIGHT FREQUENCY

【図７】 [FIG. 7]



【図8】［FIG. 8］



ELECTROOPTIC DEVICE
22 電気光学効果素子
A/O
E/O
A/O
E/O
A/O
E/O
23
21 音響光学効果素子
ACOUSTOOPTIC DEVICE
レーザパルス列
LASER PULSE TRAIN
アルゴンイオンレーザー励起のリング色素レーザー
ARGON ION LASER PUMPED RING-DYE LASER
20
共振器 13
RESONATOR
12
10
冷却装置
CRYOSTAT
11
希土類イオン分散結晶
CRYSTAL OF DISPERSED REAR-EARTH ION
14 光検出器
PHOTODETECTOR
パルス高周波磁場駆動装置
15
PULSE HIGH FREQUENCY MAGNETIC FIELD DRIVER
静磁場印加電源
16
STATIC MAGNETIC FIELD APPLYING POWER SUPPLY

[Document] ABSTRACT

[Abstract]

[Object] To provide a practical quantum information processing method capable of distinguishing and defining qubits by frequency regions regardless of spatial positions of the qubits, requiring no wiring or fine patterning process, obtaining a high scale of integration and high scalability of qubits, and good coherency.

[Means for Achieving the Object] A quantum information processing method which expresses information by quantum states of a plurality of physical systems each having at least three energy states, the method characterized by comprising: two transitions of transitions between respective energy states of each physical system being optically allowed, and expressing bit information of each physical system by a quantum state expressed by either one of two states constituting a remaining transition or by both superposition states; irradiating two-wavelength pulse lights corresponding to the transition energy of the two transitions in a temporarily superposed state to change the quantum state of individual physical system or the entire physical systems; and selecting a physical system to change the quantum state through a frequency of the pulse light.

[Elected Figure] None